1. Solid State Physics Review

Pure or "intrinsic" Silicon:

→ above absolute zero: small number of free e^-'s for conduction

→ $n_i \equiv$ density of these free e^-'s

n_i → "intrinsic carrier density"

$[n_i] = cm^{-3}$

$$n_i^2 = BT^3 e^{-E_G/kT}, \quad [n_i^2] = cm^{-6}$$

E_G = bandgap energy, $[E_G] = eV$

→ min energy needed to break a covalent bond in the semiconductor crystal, freeing e^-'s

E_g is a material property

material	E_g (eV)	λ	color
Si	1.12	1.106 μm	IR
Ge	0.66	1.877 μm	IR
GaAs	1.42	0.8725	IR near visible

K = Boltzmann's constant $= 8.62 \times 10^{-5}$ eV/K

T = absolute temperature in K

B = material-dependent parameter in $K^{-3} \cdot cm^{-6}$

material	B ($K^{-3} \cdot cm^{-6}$)
Si	1.08×10^{31}
Ge	2.31×10^{30}
GaAs	1.27×10^{29}

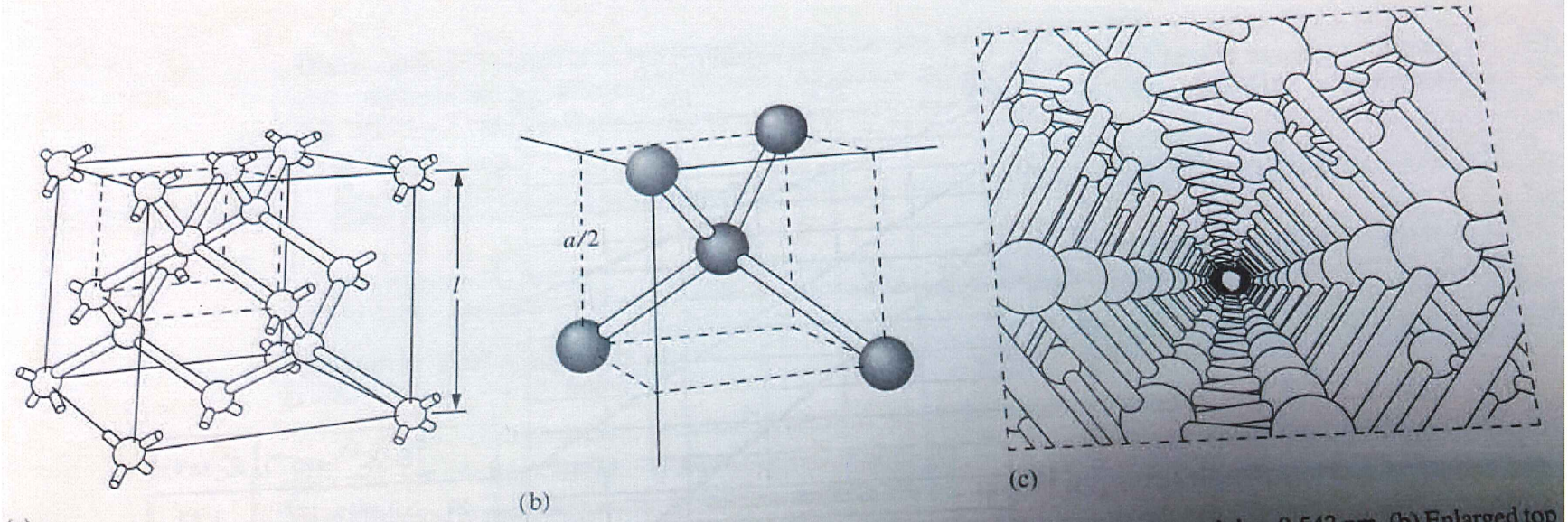


Figure 2.1 Silicon crystal lattice structure. (a) Diamond lattice unit cell. The cube side length $l = 0.543$ nm. (b) Enlarged top corner of the diamond lattice, showing the four nearest neighbors bonding within the structure. (c) View along a crystallographic axis.

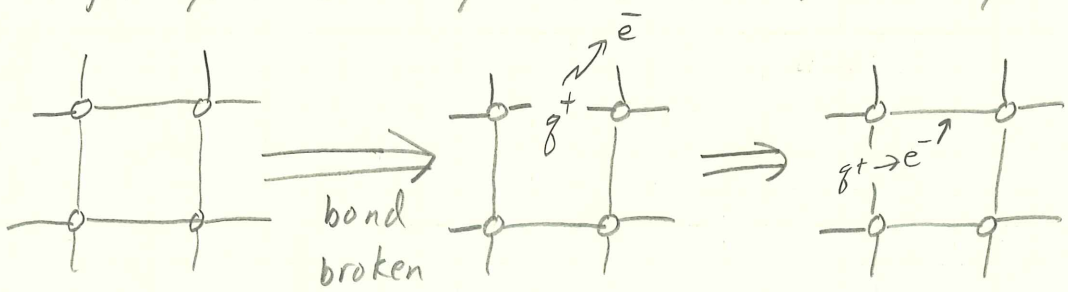
Source: (a) and (b) Adapted from Electrons and Holes in Semiconductors *by William Shockley, © 1950 by Litton Educational Publishing*
(c) Adapted from The Architecture of Molecules *by Linus Pauling © 1964 by W. H. Freeman and Company, used with permission.*

$n \equiv$ density of conduction (or free) electrons

$[n] = e^-/cm^3$

For intrinsic Si : $n_i = n$

For single crystal (monocrystalline) Si : 4 covalently bonded atoms



Energy $\geq E_G$ results in the creation of an electron-hole pair

→ electrons can move anywhere

→ holes can only move about the crystal lattice

Electrons and holes are charge carriers

$\downarrow$ $\downarrow$

$-q$ $+q$ $\Rightarrow q = 1.62 \times 10^{-19}$ C

$p \equiv$ hole density , $[p] =$ holes/cm^3

For intrinsic Si : $n_i = n = p$

$n_i^2 = pn$ → whenever there is thermal equilibrium w/o external stimulus (voltage, current, light)

Electrical resistivity $\equiv \rho = 1/\sigma$, $\sigma \equiv$ conductivity

a. <u>Drift Currents</u>

charged particles move (drift) in response to an applied electric field

→ results in a drift current, j

$j = Qv$, $[j] = A/cm^2$

$Q \equiv$ charge density, $[Q] = C/cm^3$

v = charge velocity in the electric field

↳ also called "carrier drift velocity"

$[v] = cm/s$

positive charges move in direction of the E field

negative charges move in opposite direction of the E field

For <u>low electric fields</u> : $v \propto E$ → of interest to this class

$\therefore \vec{v}_n = -\mu_n \vec{E}$

$\vec{v}_p = \mu_p \vec{E}$

where $\vec{v}_n$ = velocity of electrons

$\vec{v}_p$ = velocity of holes

μ_n = electron mobility, 1350 cm^2/V for intrinsic Si

μ_p = hole mobility, 500 cm^2/V for intrinsic Si

Notice $\mu_n > \mu_p$: e^-'s can move freely through crystal while holes can only move about the crystal through the covalent bond structure

Electron and hole drift current densities, j_n^{drift} and j_p^{drift}

$[j_n^{drift}, j_p^{drift}] = A/cm^2$

1-D vectorless equation versions:

$$j_n^{drift} = Q_n v_n = (-qn)(-\mu_n E) = qn\mu_n E$$

$$j_p^{drift} = Q_p v_p = (+qp)(+\mu_p E) = qp\mu_p E$$

Total drift current density $\equiv j_T^{drift}$

$$j_T^{drift} = j_n^{drift} + j_p^{drift} = q(n\mu_n + p\mu_p)E = \sigma E$$

σ = electrical conductivity $= q(n\mu_n + p\mu_p)$, $[\sigma] = (\Omega\text{-cm})^{-1}$

$\rho = 1/\sigma \equiv$ resistivity

<u>Note</u>: $\rho = \dfrac{E}{j_T^{drift}}$; $\Omega\cdot cm = \dfrac{V/cm}{A/cm^2}$

$$\Downarrow$$

$$R = \frac{V}{I} \rightarrow \text{Ohm's law}$$

3. <u>Doping</u>

Doping is the process of adding impurities to the intrinsic semiconductor material

<u>Donor Impurities</u> - one extra e^- in outer shell: donate e^-'s

<u>Acceptor Impurities</u> - one less e^- in outer shell: donate holes

Si: a Column IV element: 4 valence e^-'s in outer shell